EVALUATION OF SAMPLING DESIGNS FOR STREAM WATER-QUALITY TREND ANALYSIS IN CONNECTICUT

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BIOGRAPHICAL SKETCHES

Elaine Todd Trench is a hydrologist with the U.S. Geological Survey. Her recent projects have focused on statistical analysis of surface-water quality conditions in Connecticut streams, including long-term trend analysis and estimation of nutrient loads transported to Long Island Sound. She received an M.A. degree in Geology from Boston University in 1980 and a B.S. degree in Geology from Tufts University in 1973.

Aldo V. Vecchia is a statistician with the U.S. Geological Survey. His recent work includes application of time-series analysis to water-quality, hydrologic, and climatologic data from throughout the country. He received a Ph.D. degree in Statistics from Colorado State University in 1983 and has held faculty positions at Colorado School of Mines and the University of Florida.

ABSTRACT

Water-quality data for stations on the Connecticut, Naugatuck, and Saugatuck Rivers in Connecticut were analyzed using a statistical time-series model to detect trends and evaluate the sensitivity of sampling designs for monitoring future trends in water quality. This paper summarizes selected results from a study of water-quality trends and sampling designs, and expands the analysis by comparing the power of sampling designs for detecting trends in dissolved chloride, dissolved sulfate, total nitrogen, and total phosphorus at the Connecticut, Naugatuck, and Saugatuck stations.

Monthly sampling from spring to fall generally provides high trend detection power for the Connecticut River, whereas monthly sampling from winter to spring yields more information for the Naugatuck and Saugatuck Rivers. Optimal sampling designs may vary substantially for different constituents at the same station. Spring and summer sampling provides greater trend detection power for chloride and phosphorus at some stations, whereas winter and spring sampling is preferable for sulfate and nitrogen.

Results from the design analysis indicate that current (2002) monitoring schedules with 8 samples per year meet data requirements for trend analysis for some stations and constituents, but are not well-suited for the detection of trends in all situations, and may not provide the highest level of trend detection power for this sampling frequency. Most Connecticut stations have 8-sample schedules that emphasize summer sampling, but sulfate and nitrogen typically require more frequent sampling in winter and early spring for the greatest trend detection sensitivity. The greatest difference between the optimal designs and the present monitoring program is in the schedule for the Saugatuck River. The quarterly sampling schedule for this river has minimal trend detection power for all constituents evaluated. Most designs with fewer than 7 samples per year have very low trend detection power for the Saugatuck River for constituents other than chloride or sulfate.

INTRODUCTION

The U.S. Geological Survey (USGS) and the State of Connecticut have worked together since 1955 to monitor and interpret the water quality of Connecticut's rivers and streams. An expanded cooperative water-quality monitoring program with the Connecticut Department of Environmental Protection (CTDEP) began in

1974, in response to the passage of Connecticut’s Clean Water Act in 1967 and the Federal Water Pollution Control Act in 1972.

Management decisions of increasing complexity require a monitoring program that provides data for multiple purposes, including trend analysis to detect improvement or deterioration in water quality over time. As statistical methods for trend analysis and interpretation become more sophisticated and flexible, different approaches to trend analysis can provide new insights into recent and long-term (decadal or longer) water-quality conditions, as well as data requirements for future trend analysis. As part of the continuing effort to study water quality in Connecticut, the USGS and CTDEP began a cooperative project in 1998 to study long-term trends in water quality and evaluate the sensitivity and efficiency of sampling designs.

This paper evaluates selected sampling designs for the Connecticut, Naugatuck, and Saugatuck Rivers in terms of power for detecting trends in dissolved chloride, dissolved sulfate, total nitrogen, and total phosphorus concentrations. Current sampling schedules for these stations are compared to optimal designs identified by the design program.

Trends and sampling designs were analyzed for five streams in Connecticut by Trench and Vecchia (2002), including stations on the Connecticut, Salmon, Quinnipiac, Naugatuck, and Saugatuck Rivers (fig. 1, table 1). These stations are part of a network of 34 monitoring stations operated throughout Connecticut by the USGS in cooperation with the CTDEP. Dissolved chloride, dissolved sulfate, total nitrogen, total phosphorus, total organic carbon, and turbidity were included in the analysis for each station. Trends were analyzed and sampling frequencies were evaluated using a statistical time-series model developed and described by Vecchia (2000).

Table 1. Characteristics of water-quality monitoring stations selected for trend analysis and sampling design.

[Land-use data compiled by J.R. Mullaney, U.S. Geological Survey, written commun., 2001. Sampling frequency changed from monthly to 8 times per year starting in 1993. M, monthly; 8, 8 times per year (monthly in summer and bimonthly in winter); Q, quarterly; /, indicates change in sampling frequency. Land-use categories: U, urban; A, agricultural; F, forest, water, and wetlands.]

Map number (fig. 1)	Station name	Drainage area at station (square miles)	Period of water-quality record	Sampling frequency	Receiving stream for point sources	Land use (percentage of basin)		
						U	A	F
1	Connecticut River at Thompsonville, Conn.	9,660	1966–98	M/8	Yes	4.3	8.4	86.2
2	Salmon River near East Hampton, Conn.	100	1968–98	M/8/Q	No	8.4	12.3	78.8
3	Quinnipiac River at Wallingford, Conn.	115	1968–98	M/8	Yes	50.4	0.6	47.9
4	Naugatuck River at Beacon Falls, Conn.	260	1974–98	M/8	Yes	21.1	10.2	68.2
5	Saugatuck River near Redding, Conn.	21.0	1968–98	M/8/Q	No	8.1	4.5	87.5

The Connecticut River, the largest river in New England, is a regionally important resource and the major freshwater source to Long Island Sound. The drainage basin includes large undeveloped forested areas, agricultural land along the Connecticut valley, and densely populated urban areas. Both the Salmon River and Saugatuck River Basins, although primarily forested, are undergoing suburban development. The Quinnipiac and

Naugatuck Rivers have urbanized drainage basins that receive point discharges. Water-quality monitoring was initiated in these drainage basins at various times during 1966–74. Data selection and evaluation, including the effects of method changes on historical data, are described in Trench and Vecchia (2002).

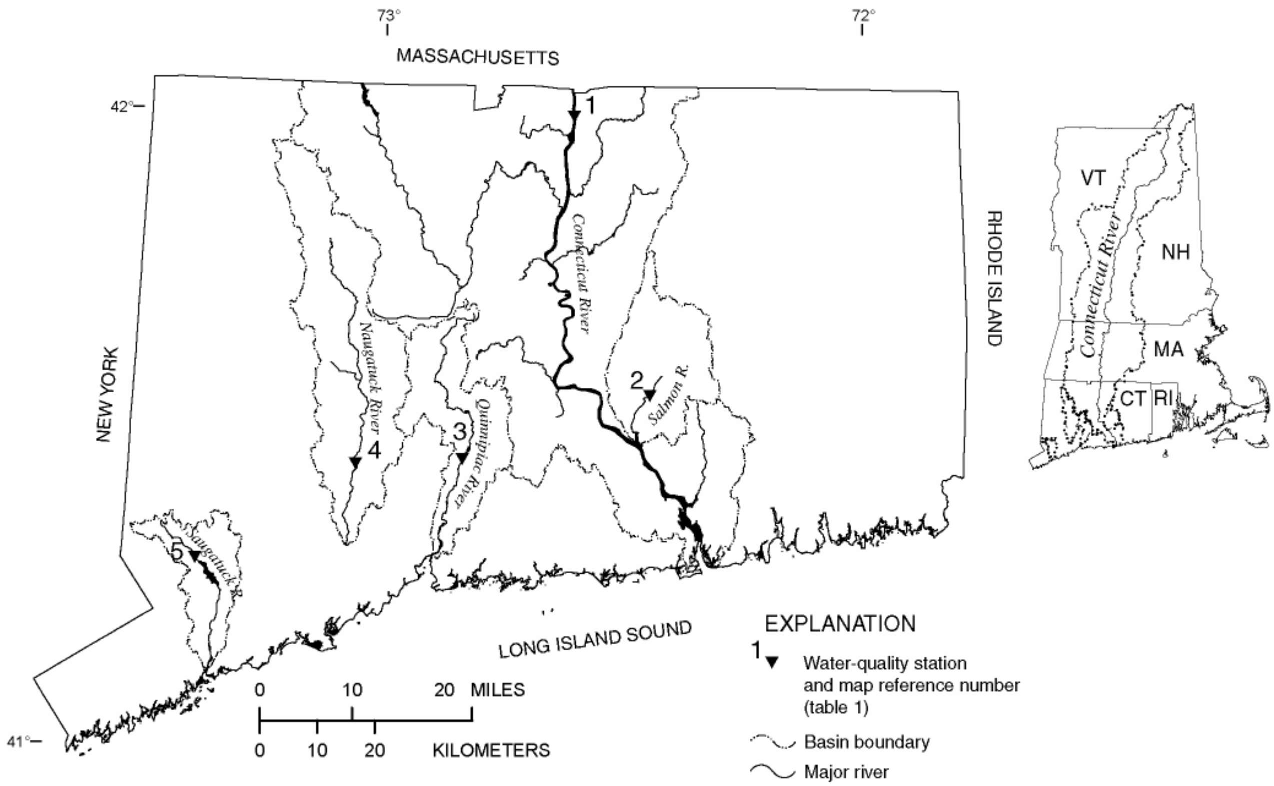

Figure 1. Map of Connecticut showing drainage basins and monitoring locations for streams evaluated with time-series analysis.

Long-term and short-term trends in the six constituents were identified for variable periods of record during the study period of 1968–98 (Trench and Vecchia, 2002). Most detected trends were not monotonic. Selected plots showing trend results for flow-adjusted concentrations are included in this paper (fig. 2). In comparing the trend plots, the actual concentration ranges in the different streams should be kept in mind.

Concentrations of dissolved chloride increased significantly during the period of record (figs. 2a-b). Upward trends in chloride concentrations in the Saugatuck River indicate that nonpoint sources probably affect chloride trends. Significant increases and decreases in dissolved sulfate concentrations were detected during one or more periods (figs. 2c-d). Typical flow-adjusted concentrations of sulfate were lower at the end of the period of record than at the beginning. Concentrations of total nitrogen increased in the Connecticut and Naugatuck Rivers during variable periods from the mid-1970's to the mid- or late-1980's, and then decreased until the early 1990's (figs. 2e-f). The most pronounced change in total phosphorus concentrations was in the Connecticut River (fig. 2g), where a highly significant downward trend was detected for the entire period of record. Total phosphorus concentrations in the Naugatuck River declined, but not as steeply as in the Connecticut River, and then increased at the end of the period of record (fig. 2h).

TIME-SERIES METHODS FOR TREND ANALYSIS AND SAMPLING DESIGN

Time-series analysis is used extensively in many fields and has become an important form of analysis in water resources (Hipel, 1985; Vecchia 1985, 2000). Time-series analysis can be used to evaluate data for nonmonotonic trends—trends that have one or more changes in slope during the evaluation period—and to detect cyclic trends. Data sets with missing data and variable sampling frequencies can be analyzed with time-series methods. Time-series analysis uses all water-quality information, even if sampling frequencies have changed one or more times during the period of record.

The time-series model requires mean daily discharge data for each day in the period analyzed and a long-term record of water-quality data. The model used in this study requires at least 60 water-quality measurements during a minimum of 15 years. Fewer than 10 percent of the measurements may be below the detection limit of each constituent considered. When carefully applied and interpreted, time-series analysis can be used to detect complex trends in concentration and evaluate the sensitivity of various sampling designs for monitoring trends in water quality.

Time-Series Modeling of Water-Quality Trends and Application to Connecticut Data

The methods used in this study to analyze water-quality trends have been described in detail by Vecchia (2000) and more briefly in Trench and Vecchia (2002). A joint time-series model for mean daily discharge and concentration is fitted to historical data for each site and each constituent. The model is used to filter out as much natural, discharge-related variability in constituent concentrations as possible before analyzing for trends. The time-series model separates the discharge and concentration data into components of annual variability, seasonal variability, and noise (deviations from the basic streamflow and water-quality conditions). In the flow-adjustment process, most of the flow-related annual and seasonal variability is removed from concentration. Thus, flow-adjusted concentrations are composed of a constant plus any trend present plus noise. Flow-adjusted concentrations can be interpreted as the concentrations that would have been observed if flow conditions had been uniform throughout the entire sampling period.

The statistical significance of detected trends depends on the statistical properties of the noise in concentration data. The noise may have a complex time-series structure that is not immediately evident from simple inspection of the data. Statistical properties of the noise in concentration data can bias estimated trends and significance levels if not properly accounted for in the trend analysis. A special type of time-series model, called a periodic autoregressive moving average (PARMA) model (Vecchia, 2000, appendix A), is used to detect and filter out the complex statistical properties of the noise in concentration data.

The time-series model in this study first was run for each constituent at each station with no trend periods specified. Trends often are apparent in plots of flow-adjusted concentrations and in the distribution of the PARMA model residuals for the no-trend model. Residuals from the PARMA model essentially are the “noise within the noise” for concentration data. After the PARMA model is applied to the noise in concentration data, and the statistical properties of the noise have been filtered out, the residuals from the PARMA model are the unexplained remnant of concentration variability, including any trends that may be present.

Several trend models were tested for each constituent at each station using linear trend periods, and, in some cases, step-trend periods, of varying lengths. Information on dates of important laboratory method changes or environmental changes such as wastewater-treatment plant upgrades also was used to select dates for trend periods and to evaluate trend results. Trend results were considered statistically significant if the p-value for the test statistic was less than or equal to 0.05. Residual plots for the selected model were examined to ensure that residuals met assumptions of random distribution with constant variance and no apparent trends.

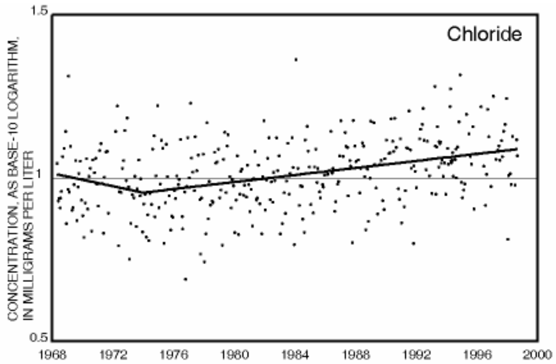

Figure 2a. Trends (lines) in flow-adjusted concentrations of dissolved chloride (points), Connecticut River at Thompsonville, 1968-98.

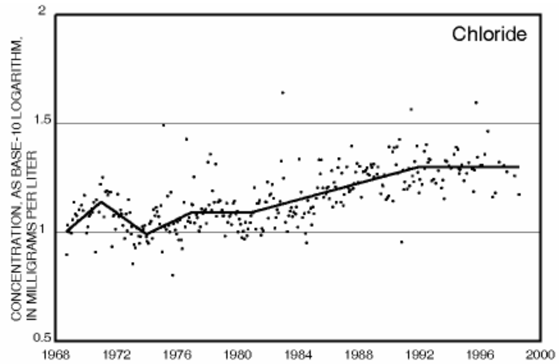

Figure 2b. Trends (lines) in flow-adjusted concentrations of dissolved chloride (points), Saugatuck River near Redding, 1968-98.

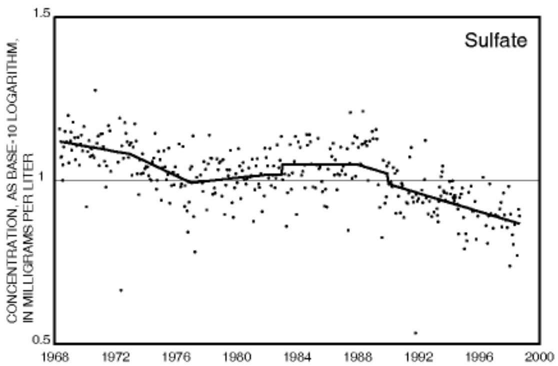

Figure 2c. Trends (lines) in flow-adjusted concentrations of dissolved sulfate (points), Connecticut River at Thompsonville, 1968-98

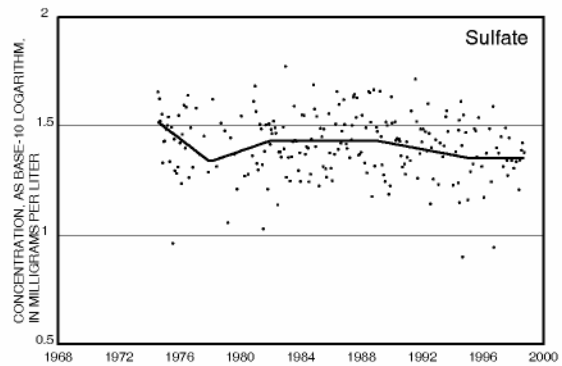

Figure 2d. Trends (lines) in flow-adjusted concentrations of dissolved sulfate (points), Naugatuck River at Beacon Falls, 1974-98.

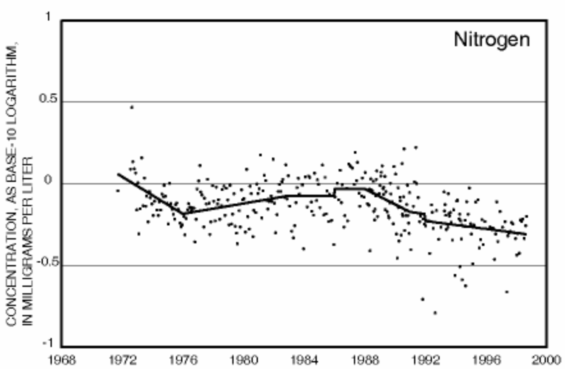

Figure 2e. Trends (lines) in flow-adjusted concentrations of total nitrogen (points), Connecticut River at Thompsonville, 1971-98.

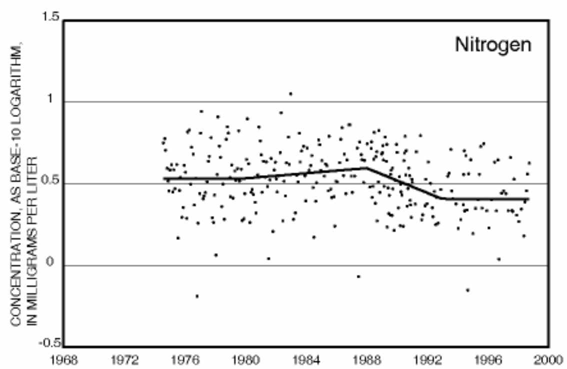

Figure 2f. Trends (lines) in flow-adjusted concentrations of total nitrogen (points), Naugatuck River at Beacon Falls, 1974-98.

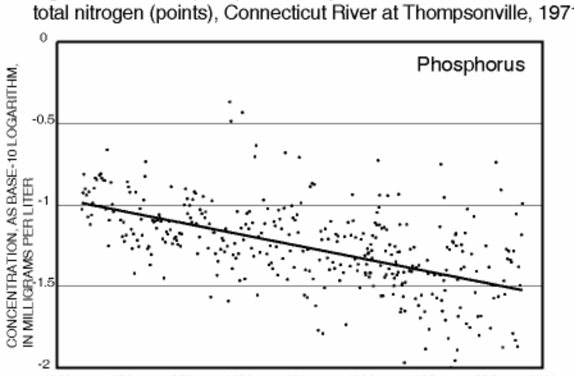

Figure 2g. Trends (lines) in flow-adjusted concentrations of total phosphorus (points), Connecticut River at Thompsonville, 1969-98.

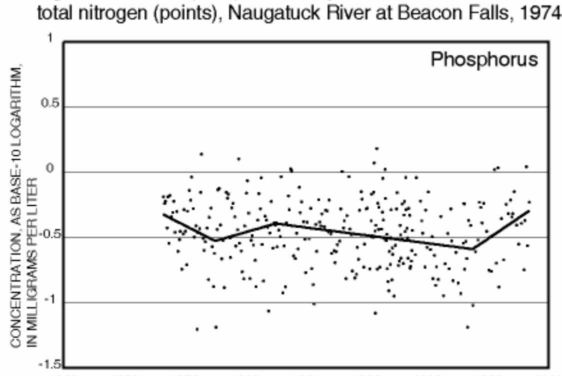

Figure 2h. Trends (lines) in flow-adjusted concentrations of total phosphorus (points), Naugatuck River at Beacon Falls, 1974-98.

Theoretical Basis for the Sampling Design Program and Application to Connecticut Data

The time-series model can be used not only to analyze historical data for trends but also to identify sampling designs (that is, sampling schedules) that maximize the sensitivity for detecting future trends in water quality (Vecchia, 2000, p. 26). The PARMA model uses information on the statistical properties of the noise in concentration to identify those months in which water-quality sampling yields the most information for trend analysis. Sampling designs can be evaluated in terms of maintaining a sampling frequency that is sufficient for future trend analysis, reducing sampling costs by eliminating samples that provide redundant information, or shifting the most frequent sampling to seasons that provide the greatest gain in information.

An optimal sampling design for a water-quality constituent is defined as the design that maximizes the sensitivity for detecting a trend of given size in that constituent for a fixed sampling cost, which usually is measured in terms of the number of samples per year. As the number of samples is increased, costs increase along with increases in sensitivity for detecting trends. However, the seasonal placement of samples during the year is an important consideration. A design with only 6 samples per year may be more sensitive than an 8-sample design with poorly selected sampling times.

Monthly sampling is the maximum allowable sampling frequency in this study based on cost considerations, with one sample per month collected at approximately the same time of month. The design program evaluates trend detection sensitivity for a set of 150 designs representing reasonable schedules for sampling frequencies ranging from 4 to 12 samples per year. Lower-cost (lower-frequency) designs are compared to the sensitivity of the monthly design to determine the best configuration of months to sample for a given cost, and to evaluate how the sensitivity of the design improves as costs increase.

The sensitivity of a sampling design can be evaluated in two equivalent ways: (1) in terms of the size of trend that can be detected for a given power, or (2) in terms of the power for detecting a trend of a given size. For this study, power is defined as the probability of detecting a trend over a 5-year design period, using a significance level of 0.05. The characteristic trend of a design is defined as the percentage increase (or decrease) in concentration that can be detected over a 5-year design period with power 0.8 (80-percent probability). For example, if the characteristic trend of a design is 50 percent, then there is a high probability (0.8) that an increase (or decrease) in concentration of 50 percent over a 5-year period will be detected using that design. The lower the characteristic trend, the more sensitive the design is for detecting trends. The higher the power of a design for a given trend size, the more sensitive the design is for detecting the trend.

EVALUATION OF SAMPLING DESIGNS

Optimal designs for dissolved chloride, dissolved sulfate, total nitrogen, and total phosphorus were examined to compare sampling requirements for these constituents. The following sections provide information on the general characteristics of the sampling design analysis; compare the power of various sampling designs for the Connecticut, Naugatuck, and Saugatuck Rivers; and evaluate current sampling schedules for these stations in terms of optimal schedules identified by the design program.

General Characteristics of Design Results

Design sensitivities for detecting a trend in sulfate for the Naugatuck River over a 5-year design period are presented in figures 3 and 4 to introduce and clarify the general characteristics of design results for all stations. In figure 3, the power to detect trends is fixed at 0.8 (80 percent probability) and the size of the characteristic (detectable) trend changes for the different designs. In figure 4, the size of the characteristic trend is fixed and the power changes for the different designs. Points on the graphs in figures 3 and 4 represent 150 specific sampling designs, numbered from left to right. Design 150, the rightmost point, corresponds to monthly sampling and is the most sensitive design. For all constituents and stations, the 12-sample design has the smallest characteristic trend for a given power of trend detection and the highest power of trend detection for a given trend size.

Characteristic trends for sulfate for the Naugatuck River vary from about 34 percent for the most sensitive design to almost 60 percent for the least sensitive design (fig. 3). The probability of detecting the characteristic trend is fixed at 0.8 for each design. Design 150, the only design with monthly sampling, has the smallest characteristic trend, about 34 percent of the flow-adjusted concentration. Designs with only four samples per year (designs 1-15) include the least sensitive designs; that is, the characteristic trends must be large in order to have an 80-percent probability of detection with this low sampling frequency.

Designs with higher sampling frequencies are not necessarily more sensitive. For example, the characteristic trend for sulfate for design 41 (one of the 6-sample designs) is about 38 percent (fig. 3). If sulfate concentrations at the end of the 5-year design period are 38 percent higher than at the beginning, there is an 80 percent chance that the increase will be detected using design 41. The characteristic trend for design 94 (one of the 9-sample designs) is about 40 percent (fig. 3). Consequently, design 94 is less sensitive for detecting a trend in sulfate than design 41, even though design 94 has 3 more samples per year than design 41. Determining which months to sample is as important as determining how many samples to collect.

The power of designs for detecting a trend in sulfate concentration on the Naugatuck River over a 5-year design period is shown in figure 4. In figure 3, the power is fixed at 0.8 and the size of the characteristic trend varies, whereas in figure 4, the size of the characteristic trend is fixed at 34 percent (the characteristic trend for monthly sampling, design 150), and the power, or probability of detection, varies. Designs with fewer than 12 samples per year have less than an 80-percent probability of detecting a change in sulfate concentration of 34 percent over the 5-year design period. Figure 4 conveys essentially the same information as figure 3, except that sensitive designs for a given sample size are now those with high power. For example, seven of the 8-sample designs have trend detection power nearly as high as design 150, and these designs correspond to the designs in figure 3 with low characteristic trends. When comparing designs for different constituents, the quantitative measure of design sensitivity represented in figure 4 has a distinct advantage over that represented in figure 3. Namely, power is dimensionless and can be plotted on the same scale for every constituent.

Design sensitivity varies among designs within a given sampling frequency, and also changes as sampling frequency increases. The characteristic trends of the most sensitive designs for sulfate on the Naugatuck River (lowest points on the graphs in fig. 3) decrease rapidly in progressing from 4 to 8 samples per year, and decrease slowly in progressing from 8 to 12 samples per year. Thus, although more designs of greater sensitivity are available as sampling frequency increases, the rate of improvement in design sensitivity generally decreases at frequencies at or above 8 samples per year. These changes in design sensitivity are shown conceptually in figure 5, which is based on results for total phosphorus for the Naugatuck River. The curves in figure 5 connect the most sensitive designs for each sampling frequency, in terms of the size of the characteristic trend (fig. 5a) and trend detection power (fig. 5b). Sampling design sensitivity increases rapidly (the curve is steep) with increased sampling at low sampling frequencies; the rate of increase in sensitivity diminishes (the curve becomes flatter) at higher sampling frequencies (figs. 3, 4, and 5). Beyond a threshhold level of necessary samples, a higher sampling frequency does not guarantee a substantial increase in the capability for detecting trends. For some constituents, designs with 8 samples per year are nearly as sensitive as design 150 with 12 samples per year. The slopes of these curves differ for each constituent at each station. In other words, the minimum level of sampling required for a reasonable level of design sensitivity is not the same for all stations and constituents.

A general characteristic of the designs, and a general concept of design evaluation, is “diminishing incremental benefits” as the number of samples, and therefore costs, increase. Diminishing incremental benefits is a property of any analysis of design efficiency, because samples with the highest incremental benefit (for example, the highest increase in power) are included first, followed by samples with lower incremental benefit. Cost-benefit analysis of designs is beyond the scope of this study; therefore, power is used as a surrogate for benefits. The overall benefit of a design is assumed to be proportional to the power for detecting a trend. Water managers can determine criteria for acceptable designs relative to the power and cost of monthly sampling.

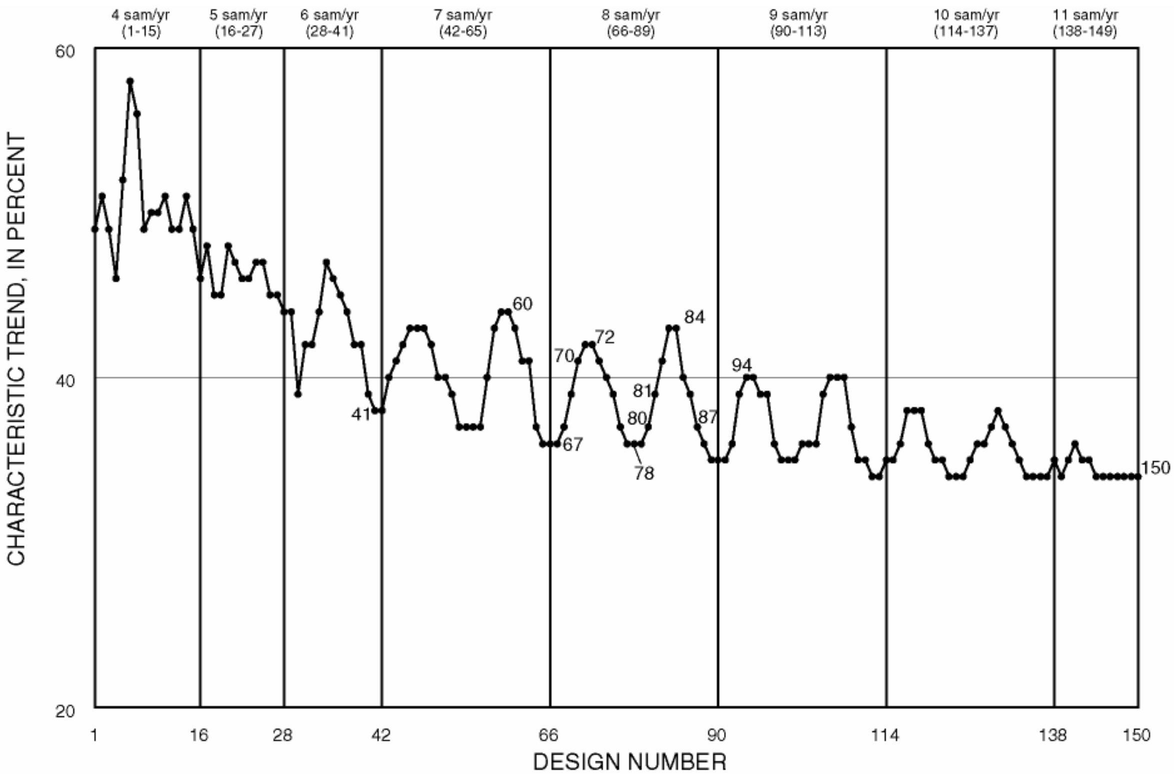

Figure 3. Magnitude of detectable (characteristic) trends in dissolved sulfate, at a fixed power of 0.8, for sample designs based on 4 through 12 samples per year, for the Naugatuck River at Beacon Falls, Conn. (Design number 150 corresponds to monthly sampling.)

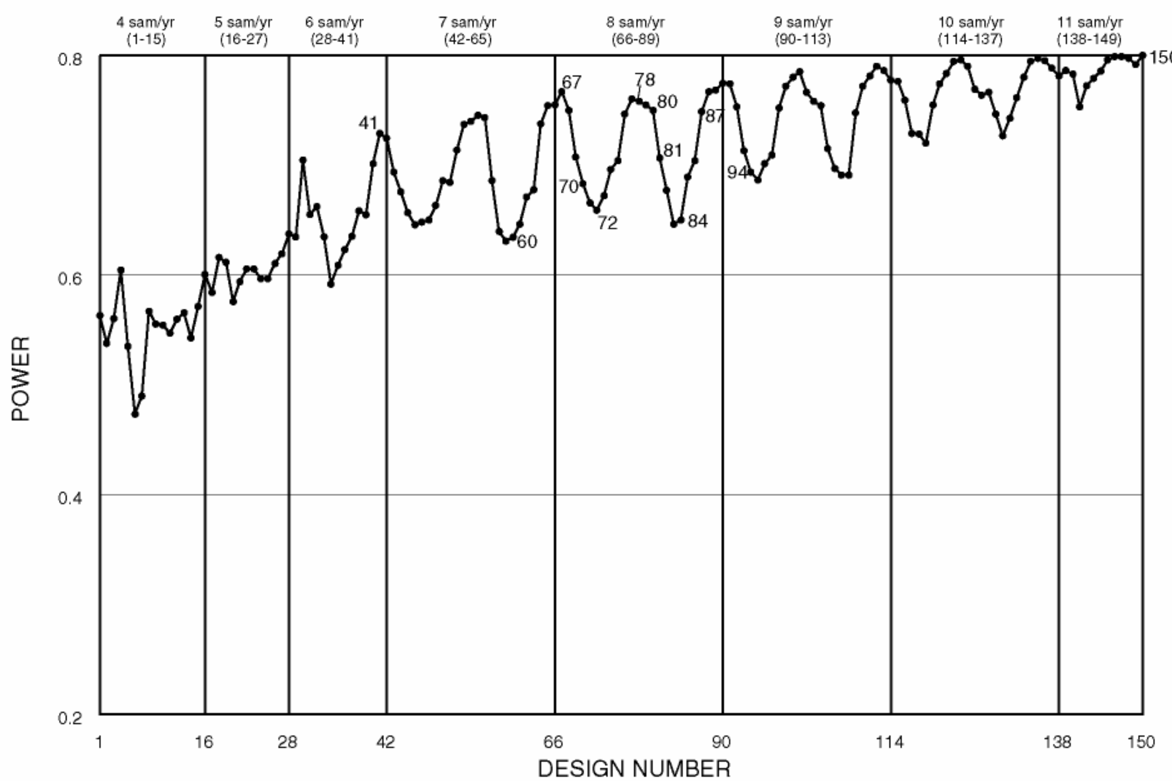

Figure 4. Power of the statistical test to detect trends in dissolved sulfate, at a fixed characteristic trend of 34 percent, for sample designs based on 4 through 12 samples per year, for the Naugatuck River at Beacon Falls, Conn. (Design number 150 corresponds to monthly sampling.)

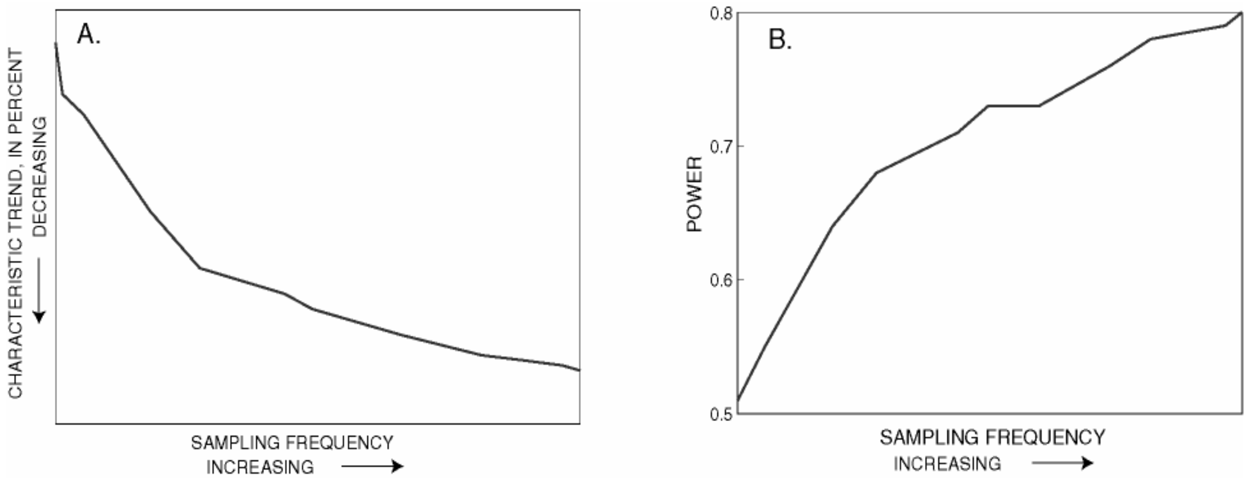

Figure 5. Conceptual plots showing changes in design sensitivity as sampling frequency increases. Plots are based on selected design results for total phosphorus for the Naugatuck River.
A. Changes in size of characteristic trend as sampling frequency increases.
B. Changes in power to detect trends as sampling frequency increases.

Evaluation of Sampling Designs for the Connecticut, Naugatuck, and Saugatuck Rivers

Selected sampling designs for the Connecticut, Naugatuck, and Saugatuck Rivers are compared in figures 6, 7, and 8. Solid boxes indicate months with water-quality samples for each of the numbered designs shown. In general, designs with higher power for trend detection are grouped at the top of the graph, and designs with lower power are grouped at the bottom.

A qualitative look at the design summary plots for the three stations (figs. 6-8) shows that the optimal time for monthly sampling is from spring to fall for the Connecticut River, and from late fall or winter to spring or summer for the Naugatuck and Saugatuck Rivers. The following discussion is based in part on examination of detailed plots for each station and constituent, an example of which is shown in figure 4.

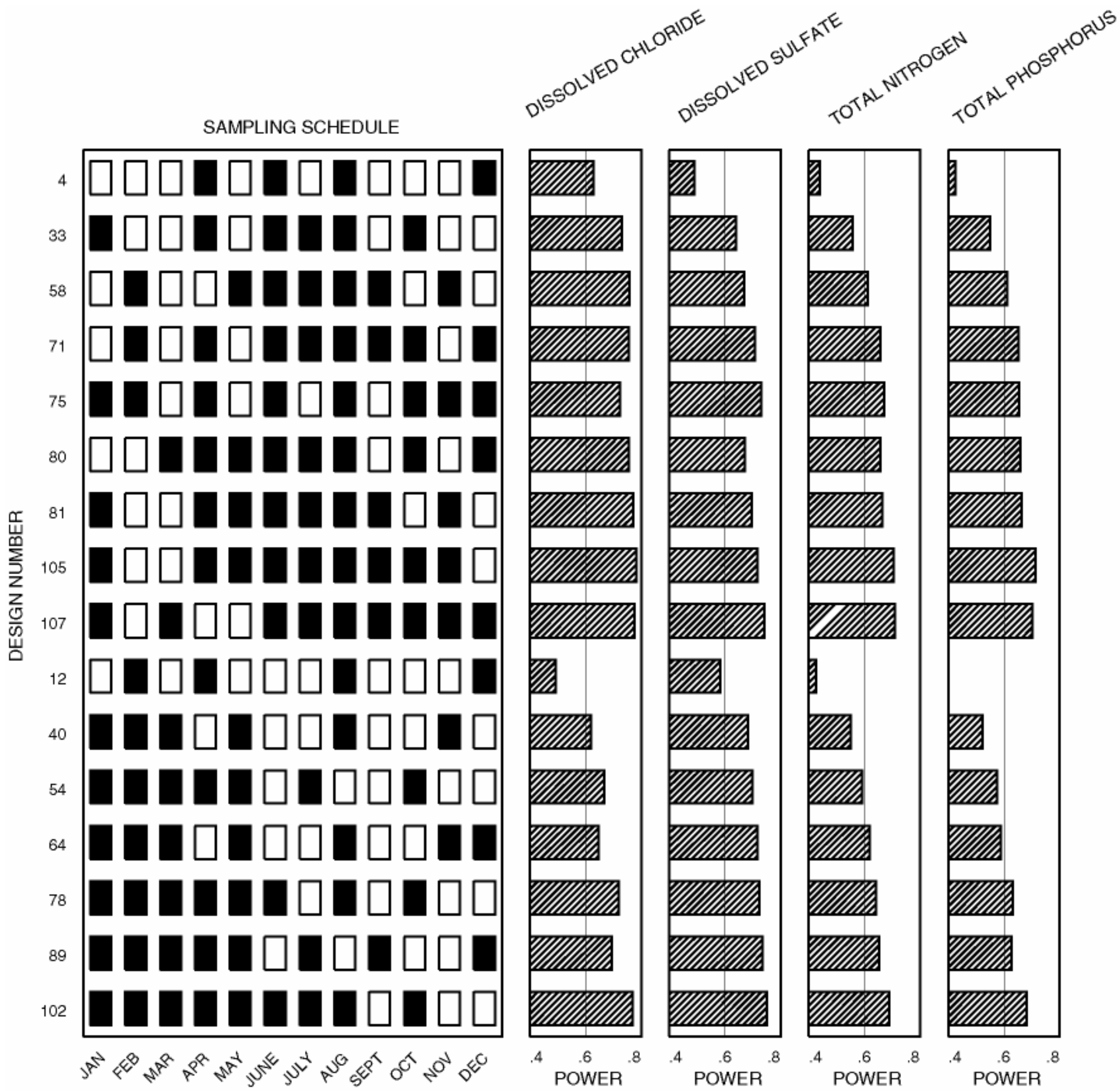

Figure 6. Comparisons of sampling schedules and trend detection power for selected monitoring designs for the Connecticut River at Thompsonville.

For the Connecticut River at Thompsonville, designs with monthly sampling during spring and summer provide moderate to high power for trend detection for three of the four constituents (fig. 6). Among the 8-sample designs, design 80 has high power for chloride and phosphorus, with moderate power for nitrogen. Design 81, with monthly sampling from April to September, is the best 8-sample design for phosphorus and also has good trend detection power for chloride and nitrogen. However, the best designs for sulfate and nitrogen include monthly sampling in winter and early spring (designs 75 and 89 in fig. 6). Sampling designs for chloride and sulfate at this station have a roughly inverse relation in terms of power. Designs with high power for chloride generally have low power for sulfate, and the reverse also is true. For example, designs 75, 78, and 89, with more winter sampling, have higher power for sulfate but lower power for chloride than other 8-sample designs. This relation also is true for other sampling frequencies.

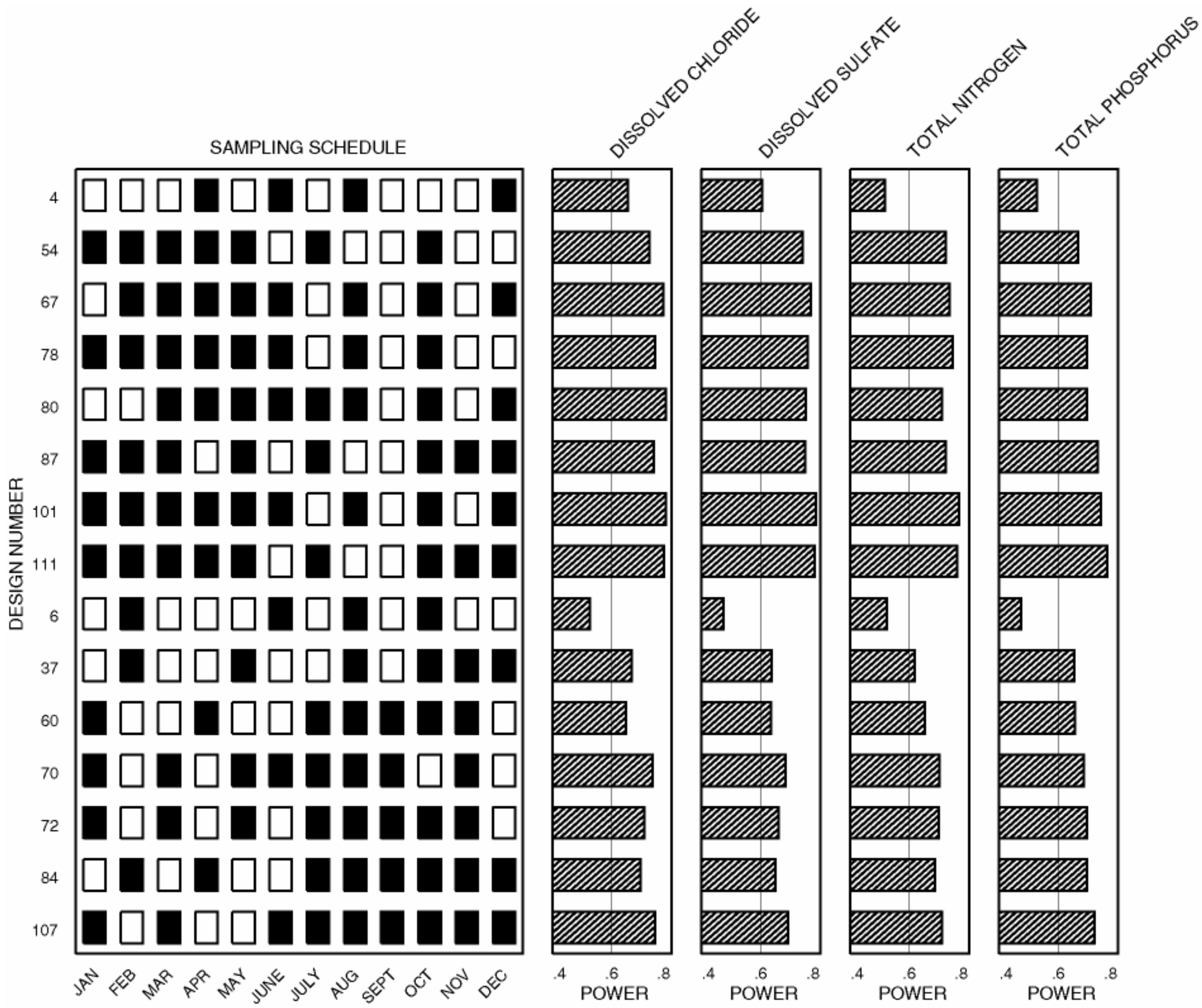

Figure 7. Comparisons of sampling schedules and trend detection power for selected monitoring designs for the Naugatuck River at Beacon Falls.

For the Naugatuck River at Beacon Falls, the more sensitive designs in each sampling frequency have monthly sampling from winter to late spring or early summer (fig. 7). Design 67, with monthly sampling from February to June, is one of the best 8-sample designs, with high power for chloride, sulfate, and nitrogen, and moderate power for phosphorus. Design 78, with monthly sampling from January to June, provides the highest power for total nitrogen. Design 87 is one of the best designs for phosphorus, with monthly sampling from October to March. The sensitivity of 8-sample designs for sulfate for the Naugatuck River is highly variable (figs. 3 and 4). Design 67 is one of the best designs for sulfate. Design 81 is only moderately sensitive for sulfate, and several 6-sample and 7-sample designs are more sensitive for sulfate than design 81 at this station (figs. 3 and 4). Design 81 is also one of the least sensitive 8-sample designs for total nitrogen. Designs 60, 72, and 84, with monthly sampling from July to November or December, are among the least sensitive 8-sample designs for the Naugatuck River, with low power for all four constituents described in this paper. Designs with low power for most constituents have monthly sampling from May to December, whereas late winter or early spring sampling is important in all the designs with high power (fig. 7).

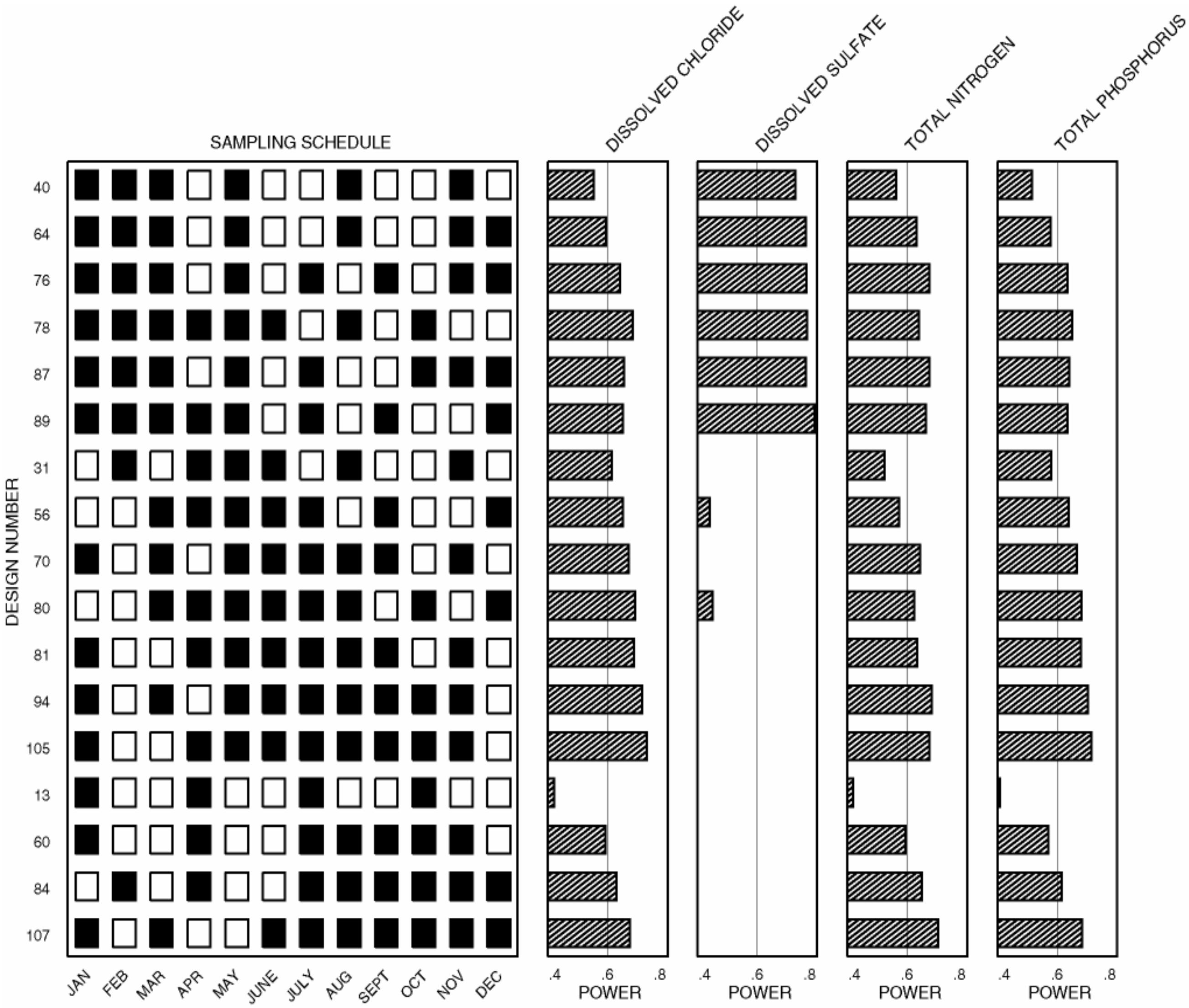

Figure 8. Comparisons of sampling schedules and trend detection power for selected monitoring designs for the Saugatuck River near Redding.

For the Saugatuck River near Redding, monthly sampling from late fall or early winter to spring generally provides the best overall trend detection power for the four constituents (fig. 8). However, designs with high power for sulfate and nitrogen generally have monthly sampling between October and June (top section of fig. 8), whereas by contrast, designs with high power for chloride and phosphorus generally have monthly sampling from March to September (middle section of fig. 8). Design 76 is the best 8-sample design for total nitrogen. Design 80 is the most sensitive 8-sample design for total phosphorus and the least sensitive for total nitrogen. Trend detection power for sulfate is extremely variable at this station. Many designs with good trend detection power for chloride and phosphorus have very low power for detecting trends in sulfate (middle section of fig. 8). Designs with monthly sampling from July to December have low power relative to other designs of the same sampling frequency (bottom section of fig. 8). All 4-sample designs have very low trend detection power (0.5 or less) for all constituents at this station.

Evaluation of Current Monitoring Program in Terms of Optimal Designs

The Connecticut and Naugatuck Rivers are monitored 8 times per year, and the Saugatuck River is monitored on a quarterly basis. All stations had a higher sampling frequency earlier in the period of record (table 1). At stations where the sampling frequency is 8 times per year, samples are collected monthly during summer to fulfill compliance monitoring requirements for streams that receive point sources, and bimonthly in winter. Selection of months for bimonthly winter sampling, and the beginning and ending months of the monthly sampling period, currently is a logistical decision, based on station location and other factors affecting field operations. Results from the design analysis indicate that the current sampling schedule meets general data requirements for long-term trend analysis for some stations and constituents, but is not well-suited for the detection of trends in all situations.

The Connecticut River station is sampled according to the schedule in design 71 (fig. 6). Design 71, with monthly sampling from June to October, has high power for detecting trends in chloride and moderately good power for sulfate, nitrogen, and phosphorus. Designs 80 and 81 have higher power for some constituents. Alternatives to the current schedule could be considered, depending on the importance of trend detection for specific constituents.

The Naugatuck River is sampled according to the schedule in design 70, with monthly sampling from May to September (fig. 7). Although not one of the least sensitive 8-sample designs, design 70 has only moderate trend detection power for chloride and low power for sulfate, nitrogen, and phosphorus relative to other 8-sample designs. Designs 78, 80, and 87 provide higher power than design 70 for two or more constituents. Additional sampling in the period from December to April is likely to improve the power for future trend detection at this station.

The Saugatuck River is sampled according to the quarterly schedule in design 13 (fig. 8). Quarterly (4-sample) designs for this station have extremely low trend detection power (0.5 or less) for the constituents evaluated in this study. Most designs with fewer than 8 samples per year have low power (less than 0.6) for constituents other than chloride or sulfate. An 8-sample design with sampling concentrated in winter and spring is likely to increase the power for future trend detection for all constituents at this station. Summer sampling to improve trend detection power for phosphorus also can be considered, depending on the importance of this constituent.

CONCLUSIONS

The evaluation of sampling designs indicates that (1) optimal seasons or months for sampling differ substantially for different constituents and stations; (2) grouped comparisons of designs with high power and low power can be used to identify seasons and months that yield the most information for trend analysis; (3) designs for the Connecticut and Saugatuck Rivers with fewer than 7 samples per year have low trend detection power for one or more constituents; (4) logistically based sampling schedules may overlook opportunities to gain more information for the same sampling frequency; (5) traditional low-flow sampling for compliance-monitoring purposes omits the most important information for dissolved sulfate and total nitrogen at some stations.

The greatest difference between the optimal designs and the present monitoring program, among the three stations evaluated here, is in the current quarterly monitoring schedule for the Saugatuck River. Quarterly (4-sample) designs for the Saugatuck River have minimal trend detection power for all constituents evaluated. Most designs with fewer than 7 or 8 samples per year have low trend detection power at this station.

The high frequency of trend detection in this study, and the high significance of many of the trends detected, indicate the variability and complexity of water-quality conditions in Connecticut. Evaluation of optimal sampling designs provides an approach for improving the efficiency of the monitoring program for detecting water-quality trends in the future. An important point is that all stations evaluated in this study were sampled on a monthly schedule during the early years of their record. This high frequency of sampling has provided the data that support the identification of optimal sampling designs.

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